REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020924 134

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

2 items enclosed

:eived: 8/19/02 10:27; -> AFRL/PRSB 4 Draco Dr. EAFB, CA ; Page 2
AUG. 19. 2002 10:01AM NO. 2466 P. 2 FILE

MEMORANDUM FOR PRR (Contractor Publication)

FROM: PROI (TI) (STINFO) 28 Apr 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0088
Philip Umholtz (Consultant), "The History of Solid Rocket Propulsion and Aerojet" (Statement A)
AIAA

THE HISTORY OF SOLID ROCKET PROPULSION AND AEROJET

Philip D. Umholtz
Consultant
Portola Valley, CA

Abstract

Much of the early history of rocket propulsion has not been the subject of organized historical documentation, and with the passage of time, and proliferation of organizational changes, the prospects for developing a clear picture of past events arc fading. These papers, and the book, upon which it is based, attempt to rectify this situation to the maximum extent possible - at least from the viewpoint of one of the major players in the field. Aerojet's role in solid propellant rocketry is described for the period of 1942 through the 1990s. The subject is addressed in terms of programs and technology, and an attempt is made to include insights into the industry, competitive, customer, and applications aspects. Origins of some of the basic enabling technologies are described, especially in terms of propellants, motor cases, and the many innovative control concepts that have given solid rockets much of their versatility.

Introduction

This paper is an outgrowth of the author's recent activities as one of several authors of a book about the history of Aerojet entitled "Aerojet: The Creative Company," and draws on material in that book. The book uses information in the public literature, and recollections of ex-employees rather than company records - and is neither approved, disapproved, nor supported by the company.

The purpose of this paper is to provide (from Aerojet's perspective)

- A very brief history of early solid propellant rocketry,
- A review of the multitude of U. S. solid propellant rocket programs,
- An overview of the associated technologies,
- And to the extent possible, their interactions.

Despite this single company bias, coverage of the entire industry since its inception in 1942 is reasonably complete. If Aerojet did not win a program competition, they, like all their major competitors, usually bid on all significant opportunities, and in many cases would win a back-up, second-source or supporting role.

Early Solid Rocketry

We have all heard of the "Chinese fire arrows" and the Congreave (gunpowder) rockets, but the origins of modern solid propellant rockets lie with a small and sometimes very informal activity under Dr. Theodore von Karman at the California Institute of Technology Guggenheim Aeronautical Laboratory (GALCIT). This group developed, built and tested many kinds of gunpowder and asphalt/perchlorate rockets, and used some of the latter to conduct the first rudimentary Jet-Assist-Take-Off (JATO) flights, starting on August 16, 1941. It was at about this time that most of the GALCIT rocket activities were moved off campus to the newly formed (March 19, 1942) Aerojet Engineering Corporation. Shortly thereafter Jack Parsons (who was one of Aerojet's five founders) suggested the use of a two-part material where the ingredients could be mixed and bonded to the inside of the metal motor walls (as opposed to having the propellant contained in a cartridge). This was the first composite case bonded solid rocket concept. The first ingredients used were asphalt and finely ground potassium perchlorate, and this case bonding idea became the fundamental basis for almost all of the modern rocket motor designs.

Shortly after this, R&D activities at Cal Tech laboratories (not GALCIT) and elsewhere (principally Thiokol) began to explore the use of rubbery compounds as the fuel/binder component for such units. Allegheny Ballistics Laboratory (ABL) and Hercules concentrated on smokeless, extruded and castable double-base (nitrocellulose and nitroglycerine) propellants, and processed the case-bonded versions thereof. Aerojet went from asphalt-based propellant to relatively rigid polyester fuels, but by 1955 had shifted to the tough and rubbery polyurethanes. These three companies were the original major competitors, and concentrated on their respective propellant families for many years. More recently, there were extensive variations of these early basic systems, and much shifting back and forth into each other's specialty fields. Also the Chemical Systems Division of United Aircraft entered the field as a major player in 1959. Other companies active in the field included Grand Central/ Lockheed, Philips Petroleum/Rocketdyne, Rocket Research, and Atlantic Research.

In the early days, the rocket motor cases were simply an exercise in how to build a metal pressure vessel with the best possible strength-to-weight ratio. In later years as the duration of firings, flame temperatures, and exhaust erosivity increased, development of sophisticated nozzle materials and configurations became a serious problem. The use of alternative and composite materials for the pressure vessel became important, such as the use of titanium and filament wound structures with increasingly sophisticated fibers and designs. The requirements for thrust vector control, precision thrust termination, dual-thrust configurations, variable thrust, and multiple start-stop concepts were added.

Solid Rocket Programs

Because of the work with the Aerojet book, the easiest way to describe the multitude of U. S. programs is to use the time line chart from the book (Fig. 1), and then to comment briefly, where possible, on programs performed by the other major companies. The time line chart information on dates, durations, program names or designations, and categorization is believed to be quite accurate for the Aerojet programs. It must be noted that in some cases, this paper reports the Aerojet portion of the effort, which may be far less than the total number of units manufactured in the overall missile program. This list also does not include follow-on parts of a missile family for which Aerojet did not participate such as Polaris but not Poseidon.

Program Categories

These programs are categorized by application (tactical or ballistic missile). These categories reflect the date and associated state of the art. For example, most of the JATOs miscellaneous boosters and ordnance programs started in the 1940s and early 1950s were able to adequately function using the asphalt and early Aeroplex (polyester) propellants. The 1949 through 1954 era saw the demand for much higher performance tactical missiles to be launched from land, sea or air. Starting with Aeroplex designs, Aerojet soon shifted to polyurethane, to polybutadiene, and then to HMX and RDX. Other advances included dual thrust and improved propellant properties, which enabled operating in a broader range of field conditions.

In 1954 the Air Force began exploring the possibility of ballistic missile applications (AFLRP - Air Force Large Solid Rocket Program, which later became Minuteman). The Navy followed much more energetically with Polaris. These commitments resulted from almost simultaneous advances in propellants, thrust vector control, thrust termination, and production capabilities as well as missile related break throughs in warheads, guidance, reentry, basing, and similar systems.

The next round of improvements was more scattered timewise, and resulted in updates to existing programs and advanced units such as the Apogee Kick Motors, and the Small ICBM. It is quite probable that the other solid rocket companies can identify similar patterns in their product lines.

Missile Families

Some of these categories include "families" of programs such as Sparrow, Minuteman, and Polaris where the overall missile system underwent a long succession of changes, but retained the same basic mission objectives. Others contain a mix of programs with greatly different goals such as the 260-in. Post Saturn Booster and the Advanced Solid Rocket Motor (ASRM), a proposed replacement for the Space Shuttle Booster.

An interesting and little known aspect of this "family" concept is that some have been active for many years. Sparrow (if you include Advanced Medium Range Air-to-Air Missile (AMRAAM)) is over 50 years old, and is still operational, including combat in Iraq. Hawk is still in use after 45 years, as is the Terrier, Tartar, Standard family. Many variations of these units in use with foreign countries were either purchased or made under license. Ballistic missile programs also have long histories. Both Polaris and Minuteman were started in the late 1950s, and their most recent configurations (Peacekeeper, Poseidon and Trident) are fully operational today.

It can be argued that the modern reincarnations in all cases are so wildly different from their early versions that they could no longer be considered part of a family. However the current products are a result of a long series of changes (some incremental and some major). Undoubtedly this is the only way that the technology could have advanced as rapidly as it has. Most programs have well developed age related replacement schedules.

Specific Categories and Programs

JATOs

In all cases JATOs were designed specifically for their stated function, and there was very little use for other purposes, as often happened with other units. The most important JATOs were the 14ASIOOO (asphalt propellant) and the 15KSIOOO (Aeroplex) units with a combined production of 512654 units, not counting the Berlin Airlift add-ons. The number and extent of military aircraft applications is very large, and some have come to light only recently. Both units were CAA (now FAA) certified for use on specific commercial propeller driven passenger carrying aircraft including the DC-3, DC-4, DC-6, Convair 240, etc. Their purpose was to act as an emergency power source in the event of engine failure, and they were most cost effective at high altitude fields such as Mexico City, Bogata, and Addis Ababa. Their price was $155 each, but there were several R&D efforts to develop lower cost versions and liquid propellant alternatives. Units with 250-lb thrust for light aircraft were developed and certified, but never saw any significant use. There was some development of a competitive extruded double-base propellant version, but production quantifies were not significant.

Miscellaneous Boosters

Some of these units were initially designed to have asphalt propellant, but all were changed to Aeroplex, and they ranged in thrust from 11,000 lb to 115,000 lb. They were used in a great number of sounding rocket, missile, aircraft, drone, sled, and similar systems. Demand for such applications has tapered off to a very low level, and now is usually met by surplus military units. Thiokol and ABL also developed and produced quite a variety of such boosters, some of which were larger than Aerojet's.

Ordnance Rockets

Aerojet never had a significant role in this field. Ordnance rockets were viewed as a commodity item similar to ammunition that held little R&D interest, the industry price competition was ferocious, and government arsenals did much of the work. The distinction between ordnance and tactical rockets is unclear, but in this study we consider ordnance rockets as unguided, 5 inches or less in diameter, and having the prospect of very high production rates.

Tactical Rockets

Aerojet participated extensively in the Sparrow, Hawk, and Tartar/Terrier/Standard program families. Examples of typical JATOs, miscellaneous boosters, and tactical rockets are shown in Figure 2.

Sparrow: This Navy concept was for a basic air-to-air, short to medium range missile with a boost-glide trajectory, and (originally) a variety of guidance/homing systems. The program started with three prime contractors, one for each of the competing guidance systems. Sparrow III under Raytheon won out. The original powerplant had a nominal rating of 1.8-sec duration and 7800-lb thrust, and was subject to numerous modifications and upgrades including several dual-thrust versions for increased range, and both larger and smaller versions. The basic powerplant and its variants were used to power the anti-radiation missile (ARM), Sea Sparrow, Shrike, Improved Shrike, Skyflash (UK), and Skipper 11. AMRAAM serves the same role as Sparrow, but has only a 7-in. diameter with considerably improved performance resulting from improved propellants and its boost/cruise dual-thrust arrangement. Aerojet developed and produced several thousand of the original shell and tube 8-in. diameter motors. However, most of the original Sparrow production was in the form of a storable liquid propellant motor that was interchangeable with the solid.

Falcon. The Air Force Falcon started slightly earlier than Sparrow, and had an almost identical role. Hughes was the prime contractor and Thiokol supplied the powerplant. Most of the Falcons were 6.6 inches in diameter, went through many variations, and are believed to have merged with or be superseded by AMRAAM. Hughes is the prime contractor for Falcon, Phoenix, and AMRAAM and there are many guidance and system similarities in these programs.

Sidewinder. This was a Navy program to achieve a simple, low cost, short range, air-to-air missile based on a standard 5-in. ordnance rocket that used an external double-base propellant grain for propulsion. Essentially all aspects of the missile were developed and initially produced at the Naval Ordnance Test Station. These included the rocket motor, infrared seeker, guidance and control system, auxiliary power system, and the warhead. As with all such missiles, there was continual upgrading of all of the systems and components. The missile was very successful and is still in use. The missile was fielded in the early 1950s, but components had been under development years earlier. Very large numbers were produced, and the missile is in use with many air forces around the world. A much larger version (Diamondback) of similar concept was considered, but never implemented.

Aerowolf. This Aerojet missile is believed to be the earliest of any of these air-to-air concepts, and was a completely in-house project (company funded). It used all purpose designed components and systems, and was very similar to Sidewinder except that it was only 3.5 inches in diameter and claimed slightly better performance in essentially all parameters. It never reached the stage of complete assembly of a working breadboard model.

Genie, Eagle, Phoenix. Several much larger (15 to 17.5 in. diameter) air-to-air missiles appeared in the mid to late 1950s including Genie, Eagle, and Phoenix. Genie was an unguided missile with a nuclear warhead. Several thousand were produced, and the only full system test was quite successful. Eagle and Phoenix were based on the need for interception of multiple enemy aircraft at extreme ranges. The launching aircraft could engage six targets simultaneously, and could "launch and leave". The missile could operate in any weather and at any altitude, and could "look down/shoot down". This called for an extremely high performance propulsion system. In the Eagle this was accomplished using two stages, the latest propellants, and sophisticated multiple swiveling nozzles for thrust vector control (TVC). This technology preceded the very similar TVC used on Polaris. The resulting missile was very large. This entire approach to protecting the fleet with low speed, loitering was abandoned and the Eagle never reached operational status. The reason cited for cancellation was excessive cost.

Several years later the issue was revisited in the Phoenix program, which met all of the performance objectives with a single dual-thrust rocket motor. These missiles achieved four kills on a six by six engagement that started over 150 miles away. Both Aerojet and Rocketdyne developed and produced successful motors. The missile is still fully operational, and it is believed that production of the Rocketdyne version is continuing. This is usually thought to be by far the most effective and expensive air-to-air missile ever developed.

Surface-to-Air Tactical Missiles

This category may be further subdivided to include systems whose objective is to attack aircraft, and those that attempt to defeat incoming warheads. In more or less chronological order, the "anti-aircraft" types include: Nike (Ajax and Hercules), the Navy group of Tartar/Terrier/ Talos /Navy Standard Missile, Hawk, Patriot, THAAD (to some extent), and several handheld short range systems. Aerojet had a significant position in only two of these families, Hawk and Tartar/Terrier/Standard.

Hawk. Hawk is the only Army program for which Aerojet was the primary propulsion contractor from its inception to the present time. The Hawk motor started as a dual-thrust unit, underwent only one significant upgrade (to Improved Hawk), and is still in limited production (inventory replacement). Total production as of 1995 was more than 43,000 units. It is in service in many parts of the world, and has been produced under license by several countries including Italy and France.

Standard. The Standard Navy Terrier/Tartar/Standard family started at about the same time as Sparrow and probably included an even greater number of upgrades and variants than did Sparrow. There were single and dual thrust versions, as well as two-stage designs, and variations that could be used (in parallel programs) for ship-to-ship and underwater launching and/or targeting (ASROC and SUBROC). One thing that was common to a these systems was the strict adherence to 14 inches maximum diameter - mandated by the complex and costly shipboard storage (magazine) systems, and torpedo tube limitations. During the Vietnam War the 8-in. diameter Shrike was in short supply and was not effective against all targets. As a result, the larger Standard was modified to perform as the Standard Anti-Radiation Missile (ARM), and later as the High-speed Anti Radiation Missile (HARM). These versions proved to be reasonably successful.

Surface-to-Air Missiles – Nike, et al.

Nike. The earliest surface-to-air missiles, mainly the Nike family, were designed to prevent relatively low speed Russian bombers from attacking U.S. cities and military targets. Most of these missiles had two stages and used a variety of powerplants and underwent several upgrades. Limitations in detection and command-and-control systems resulted in the need for very rapid acceleration and short time to the target. That problem is with us today in defending against short range SSMs (surface-to-surface missiles such as Scud and Silkworm). Also, the huge area and number of targets needing protection resulted in very large numbers of missiles, and many large detection and guidance installations. Some of Aerojet's early miscellaneous boosters served as Nike Ajax boosters, and the earliest sustainers used Aerojet liquid propellant motors. Despite numerous attempts to develop suitable propellants and/or motors for these and subsequent higher performance SAMs, Aerojet was unable to win any of these program competitions.

Hercules. Nike Hercules overlapped with and superseded Ajax, and was many times more costly and complex. Much of the Nike concept was based on nuclear warheads (currently out of favor), Russian bombers became a lot faster and fewer in number and the main targets became ballistic warheads. The Nike systems were finally deactivated, and after a long period of relative inactivity, Patriot was developed and deployed. This was a much shorter-range system, but still well above Hawk capabilities. Patriot is currently undergoing serious upgrading, and a much higher capability system THAAD (Theater High Altitude Area Defense System) is under consideration. With forward basing, this system is claimed to be able to attack ICBMs in their launch phase or (from other bases) the warheads upon reentry, and somewhat incidentally, much less challenging targets. Serious advances in propulsion technology are a prime prerequisite.

Surface-to-Air Anti ICBM Missiles

Several approaches toward intercepting ICBM warheads were tried over the years, but none could be considered a success. The first was Nike Zeus, which tried to use the huge Hercules infrastructure. This became Nike X, followed by a confusing sequence and combinations of Safeguard, Spartan, Sprint, and Sentinel. Some were designed to intercept at short range, and some at long range. There were variations on each concept. Spartan was the only one to reach operational status, and was canceled the next day. After a long period of relative inactivity, the national missile defense concept was introduced. This too lost momentum, but now might be regaining some interest. Aerojet did develop at least one new propellant and design for several applications.

Surface-to-Surface Battlefield Missiles

The Army has been the cognizant military service for all of these, which include Corporal, Honest John, Little John, Sergeant, LaCrosse, Lance, and Pershing. Thiokol and ABL/Hercules were the powerplant suppliers. Most of these programs reached substantial production quantities. All of these systems were capable of carrying nuclear warheads, so there was no foreign production.

Air-to-Surface Missiles (ASMs)

These systems constituted a relatively small portion of the tactical missile category, and included systems such as Gargoyle, Bullpup, Rebel, Maverick and the Short-Range Attack Missile (SRAM). Most were simply glide bombs with various levels of propulsion, and various types of guidance or homing. SRAM was a much more interesting concept. This missile was carried by B-52s and was to be used to clear a path through enemy air defense systems. Up to 36 nuclear tipped missiles could be carried in one aircraft. The ASM required a very advanced propulsion unit, even by current standards – a graphite/epoxy case, HTPB propellant, dual thrust and a multiple stop-start capability. Aerojet and Lockheed Propulsion developed early units, but Thiokol won the major production contracts.

Miscellaneous Solid Rockets

The number of miscellaneous rockets produced by Aerojet is quite lengthy, hence only a few are noted in Figure 1. It is almost certain that the same situation prevails in the other rocket companies. Accordingly only a few of the most interesting examples will be mentioned.

As part of the Star Wars concept for attacking incoming ballistic missile warheads, one plan was to simply scatter a large number of small inert objects into their path. The extremely high impact velocity would obviate the need for any kind of warhead. This idea was dubbed "Brilliant Pebbles", and most of the development work went into extremely sophisticated, ultra-high-energy liquid propellant powerplants that would move the kill vehicle to its proper position. Aerojet also did considerable amounts of development work on solid propellant versions, but program funding was cut off before complete powerplants could be demonstrated.

Although listed as a separate category (Space Vehicle Motors), these units could easily be considered as part of the miscellaneous group. All were designed for the apogee kick application that called for the maximum possible performance (delta V, i.e., a combination of mass fraction and propellant specific impulse), and total impulse flexibility. Five basic sizes were developed, and they ranged from 158 to 1557 pounds of total motor weight. More than 58 units were built and flown during the 1970s.

Ballistic Missiles

Aerojet participated in essentially all of the ballistic missile propulsion systems, the only notable exceptions being Poseidon and Trident. The missile families in chronological order of initiation include Minuteman, Polaris, Skybolt, Peacekeeper and Small ICBM. Industry and the military services began serious studies of solid propellant IRBMs, ICBMs, and SLBMs around 1953. The Air Force initiated the Large Solid Rocket Feasibility Program (AFLRP) in 1954 to explore some of the major unknowns involved in scaling rockets up to much larger sizes, and to evaluate new control concepts and production possibilities. This took the form of two 1-year competitions involving Grand Central/Lockheed, Phillips Petroleum/Rocketdyne, and Aerojet for the first year, and Thiokol, Hercules, and Aerojet for the second year. Next, several rounds of R&D contracts, which focused increasingly on a specific missile configuration, were completed, and the official Minuteman development program was started in 1959.

One very significant feature of the thrust vector control (TVC), thrust termination (TT), and trajectory part of the AFLRP work at Aerojet was the realization that solid rockets could be flown over a trajectory that was drastically different from that of the existing liquid propellant ICBMs and IRBMs. Solids (because of their very strong chamber structure) could accelerate out of the silo at more than 2 gs, pitch over toward the target very rapidly, and go through the regime of maximum dynamic pressure at a significant pitch angle. Since this increased its range almost 20% compared to the liquid trajectory, this concept was used in all subsequent systems.

Minuteman. The three major rocket companies (and later United Technologies Corp - UTC) set out on an almost unbelievably complex set of research, R&D, and production activities that finally culminated in the successful delivery of the propulsion part of the Minuteman weapon system. There were three propulsion stages and three major as well as several minor upgrades (Minuteman I, II, and III, and various wings thereof). There was also an environment of continual invention and technological advances, as well as customer driven changes, and retrofitting. And the customer usually had back-up and parallel programs for most of the stages. Some appreciation for this program complexity can be gained from the following Figure 3 that at least partially documents the extent of the various motor manufacturers' deliverables. Aerojet numerical data are shown, and it is hoped that similar information can be developed for the others. Finally, it was found that many types of solid propellant can suffer a very gradual deterioration, and that the second and third stage motors would have to be refurbished (or replaced) periodically. The first round of this program was recently completed, and the second round has been started.

In somewhat oversimplified terms, 800 Minuteman I missiles were deployed by 1965, an additional 200 Minuteman IIs were deployed by 1967, and by 1975, earlier units were replaced by Minuteman III's. The most important of the many changes shown in Figure 3 were in the third stage of Minuteman III, which went from a 37-in. diameter to the full Stage Two's 52-in. diameter, and used a single fixed nozzle with liquid injection TVC. Aerojet produced a total of about 3,373 units, and reached a maximum production rate of 610 units in one year.

Polaris. The Navy's Submarine Launched Ballistic Missile (SLBM) concept, started in 1955, accelerated much more rapidly toward an operational missile system than did Minuteman. It is suspected, but not known, that a few people high in government were aware that the Russians already had several operational SLBM vessels. This fact may have accounted for the almost crisis pace of the entire program. Initial efforts were directed toward a Joint Army - Navy IRBM called the Jupiter-S (for solid). This design was much too bulky for the SLBM concept (only four missiles could be fit into the selected submarines, but the Polaris designs allowed 16). As a result, the idea of a joint missile was abandoned, and Polaris began its development and long succession of upgrades to its present Triton configuration.

The Fleet Ballistic Missile (FBM) program was like the Minuteman program in that its propulsion system underwent a large number of upgrades and developmental changes, and there was considerable switching between contractors for the different stages. In addition, the missile went from a 2-stage configuration to a 3-stage configuration. The major variations included Polaris A-1, A-2, A-3, Poseidon C-3, and Trident C-4 and D-5. See Figure 4. The missile grew from 54-in. diameter and a 1200-nm range to 74 in. and then to an 8-in. diameter with a more than 4000-nm range. Because of its submarine launching and operating requirements, the Polaris propulsion system encountered even more complexities than Minuteman.

The accelerated development of the entire program encountered different technical problems and resulted in different solutions than for the Minuteman system. Also the organizational approach was quite different from the start. The Polaris approach was to have a completely autonomous and self-sufficient organization and staff, to emphasize extremely detailed and real-time management and documentation, and to address the aspect of extreme urgency. The Minuteman project structure eventually reflected a similar approach. Although this was not necessarily the most economic way to run a program, it was certainly the most effective. The first operational patrol of a Polaris submarine started on 15 November 1960, approximately five years after the start of missile propulsion development. The first launch and successful nuclear warhead detonation occurred 6 May 1962. In general terms, Polaris started out later than Minuteman, but finished about one year earlier.

An interesting sidelight to this program is that the U.S. sold Polaris A-3 missiles (less warheads) to the U.K. starting late in 1980. These were later upgraded to Trident I (D-4s) and then to Trident 11 (D-5s) - enough to outfit four submarines. Aerojet participated during the A-3 phase.

Aerojet's role was the extensive early development and production of the A-1, A-2, and A-3 first stage motors, and some of the A-1 second stages. When the program began, and for some time thereafter, Hercules double-base propellants were viewed as having higher performance, but had a higher explosives classification that precluded their use on board submarines. This restriction was removed, and the Hercules second stage motors were used from then on. Aerojet produced about 1300 first stage and 42 second-stage motors for Polaris. Thiokol and Hercules supplied the propulsion for Poseidon and Trident.

Skybolt: Although this missile could be classified as an ASM, it was planned to fly a ballistic trajectory, had a range of about 1100 miles, and was to be used in a strategic role. Thus it will be grouped with the ballistic missiles. Despite the availability of Atlas, Titan, Minuteman, Polaris, as well as the Thor and Jupiter IRBMs, in 1959 the Air Force felt it necessary to initiate development of this missile to be launched from B-52s. Skybolt used a single stage motor with about a 35-in. diameter and 25,000 lb thrust. Aerojet was the sole supplier, and produced 28 motors before the program was canceled in 1961. The motors performed satisfactorily, but the program never had a strong sponsor or a sufficiently robust reason to exist.

Peacekeeper: In 1973 the Air Force felt the need to develop a solid propellant heavy lift ICBM (Peacekeeper or MX) to supplement Minuteman, match Russian capabilities in this realm, and possibly take the place of Titan II if it ever was to be deactivated. It was to be a three-stage missile using the latest technology in all conceivable parts of the system, and fit into the modified Minuteman silos. This was found to be possible despite MM's 65-in. diameter and Peacekeeper's 92-in. diameter. The various features shown in the nozzle drawing in Figure 4 can illustrate the level of design sophistication. The entire program met all sorts of political and pacifist opposition, including long delays in funding. Aerojet won one of the 2-year initial development contracts, and finally won the production contract to manufacture the second stage. During its production from 1983 to 1993, about 150 units were produced installed in 50 modified Minuteman silos.

Midgetman (Small ICBM: In the late 1970s there was growing concern about the vulnerability of silo-based ICBMs. The Air Force explored various concepts for solving this problem. One of these, the Midgetman, was small enough for various types of mobile basing. In 1983, Aerojet won one of the small preliminary development programs for a very advanced rocket motor design with a carbon fiber composite case, carbon fiber nozzle, and polyethylene glycol nitroglycerin (PEGNG) propellant. Aerojet won only the back-up role for the second stage, but this development proceeded quite successfully through initial flight test. At this point President Bush unilaterally canceled the program as part of the U.S. political posture of arms limitation.

Space Boosters

The use of solid propellant rockets as space boosters is covered with great detail and clarity in the AIAA Paper AIAA-94-3057, "The History of Large Solid Rocket Motor Development in the United States" by Wilbur C. Andrepont of United Technologies Corporation and Rafael M. Felix of Sparta, Incorporated. No attempt will be made to repeat that effort, as it is quite complete and detailed in its coverage of this complex chain of events. We will simply note that Aerojet had three pivotal programs in this field: (1) a major role in the earliest large diameter development efforts (the 100-in. segmented motor feasibility program), (2) complete and successful early development of the monumental 260-in. space booster program, and (3) the on-time and on-budget development program for the Advanced Solid Rocket Motor (ASRM) replacement for the Space Shuttle booster. NASA canceled the latter two programs ostensibly for funding reasons. To the more technologically minded participants, both actions constituted a retreat to the existing technologies and organizational structures.

Solid Rocket Technology

Propellant Families.

Early post asphalt propellant systems included several based on thermoplastic binders such as plasticized ethyl cellulose, polyisobutylene, polyvinyl acetate, and polyvinyl chloride. There may still be a few specialty uses, but such systems have essentially disappeared. Later thermosets included polyesters, polysulfide, and butadiene. In very general terms Aerojet concentrated on the polyurethane (PU) family, Thiokol favored polybutadiene (PB), and Hercules continued their interest in double-base formulations including RDX, HMX, etc. Although each of the companies crossed over into their competitors' fields on many occasions, they were often limited by long-term commitments, experience and production facility considerations. A broadly based chart tracing the relationships and progression of propellant families as well as their steady climb in performance, is shown in Figures 5 and 6.

The major and fundamental advance in propellant evaluation occurred when the development process changed from trial and error corresponding with various mixtures to application of scientific principles of polymer chemistry to generate entirely new binders. The most versatile of these was the polyurethane family, which was compatible with the addition of aluminum powder that made it possible to change the ballistic performance and physical properties of new propellants and led to the advanced hydrocarbon polyurethane, hydroxy-terminated polybutadiene (HTPB).

An interesting note regarding the origins of polyurethanes was the fact that they originally required a relatively high temperature production process. This would be very risky when done in the presence of a high-energy oxidizer. Fortunately Aerojet was a long-term participant in a Navy sponsored fundamental research project on nitropolymers. A clue to a low temperature reaction was discovered during this program that allowed early implementation of much of polyurethane development effort. All this changed with the use of plasticizers that made the compositions more processible. Plasticizers thus became a standard component in all propellants. Some of the classes of propellants that evolved and their performance improvements are shown in Figures 5 and 6.

Many other parameters other than specific impulse (Isp) are very important to the end product missile systems often resulted in unexpected needs for changes in propellant selection. As an example, the amount of smoke in the exhaust is crucial for an air-to-surface missile wherein the pilot launching the missile has to guide it to the target (e.g., Bull Pup and Maverick). Similarly, the lowest temperature that a missile powerplant can survive without propellant shrinkage cracking, is an absolute limitation for many air or surface launched systems as well as space launched powerplants. Also, resistance to gunfire, droppage, and other impact conditions is important. Combustion instability occurs in solid rockets as well as in liquids, but in recent years methods (other than just the addition of powdered aluminum) have been developed for anticipating and correcting this problem. All of these variables usually result in significant propellant optimization efforts in a typical rocket motor development program.

Atlantic Research Corporation made the extremely important discovery that the addition of powdered aluminum in place of some of the oxidizer could increase specific impulse as much as 15%, and even beryllium was tried. One of the earliest problems encountered was how to get the maximum amount of oxidizer mixed in with the fuel (binder), and still have adequate mechanical strength. Oxidizer grinding changes produced a wide variety of particle sizes and mixtures. Various wetting approaches were developed. In the Polaris program, nitropolymers were developed wherein the fuel included part of the oxidizer. Rather than attempt to cover the multitude of new propellant developments in recent years, the reader should peruse the excellent paper on this topic AIAA-93-1783, "My Memoirs of Solid Propellant Development at the Air Force Rocket Propulsion Laboratory" by R. Geisler.

Propellant Grain Design

In a fundamental case bonded grain design there is a hole down the center of the propellant, and the hot gases proceed down this passage and out of the nozzle. As burning progresses more and more burning surface is exposed, and pressure and resulting thrust may end up being several times the initial values. If the central perforation is star shaped in cross section, the tips of the star burn away, reducing the exposed area and resulting in a relatively constant rate of gas evolution.

These geometric details can be adjusted both in cross section and longitudinally to tailor the thrust time curve to a wide variety of mission requirements. Layers of propellants with different burning rates can give the designer additional options. This boost-sustain thrust time curve (dual thrust) is common in most modem missiles that operate in the atmosphere, and usually results in a significant increase in range. In the earliest days of tactical missiles, these design variables were optimized by interminable, tedious computations using desk calculators.

Propellant Production

Early asphalt based rockets were actually made by manually pouring and stirring ground oxidizer into heated asphalt. This soon gave way to commercial bread dough mixers, followed by larger and much sturdier mixers based on those used in the tire industry. Fatalities occurred in both oxidizer grinding and in propellant mixing before the industry finally developed remotely operated and much more sophisticated processes. At the start of the Polaris program it became apparent that production of the nitropolymers might easily become a high production process for very specialized compounds, and that a continuous processing plant would be needed. Such a plant was designed and built, and it was the first of its kind - certainly for such materials. A logical extension was the development and building of a continuous mixing plant wherein the fuel, oxidizer and other propellant constituents were mixed continuously in a form of screw extruder that emptied directly into the rocket motor case. This was highly desirable in terms of safety, quality control, and the ability to produce huge amounts of propellant in a short time. In a rocket motor the size of the 260-inch SRM, it was found that a continuous mixer and two batch processors could be run simultaneously, feeding the same chamber.

Ignition

Propellant ignition underwent significant developmental evolution. Black powder was the basic ingredient of many of the earliest units.

Aerojet developed Alclo (a mixture of aluminum powder and potassium perchlorate compressed into aspirin sized pellets). The pellets were contained in a wire mesh basket and initiated by a squib and/or a small charge of black powder. These igniters were widely used at Aerojet because of their low brisance and high flame temperature, but infrequently used by others in the industry. Pyrogen rocket type igniters are now an industry standard because they can be designed accurately and perform consistently. A relatively recent requirement that has been met is for a motor to stop and restart on command for at least one or two cycles. This is obviously much more complex than simple ignition and thrust termination.

Explosive Classification

The various categories assigned to solid propellant rockets depend on several characteristics such as the extent of exposure to fire before ignition, the propensity for sympathetic explosion if nearby units explode, or whether the propellant will simply explode rather than detonate. This seemingly innocuous requirement can have serious consequences in terms of facilities and table of distance considerations. In several instances it caused Aerojet to acquire large blocks of land in remote locations for both production and test/storage operations. In the early JATO days it finally drove home the need to purchase the Sacramento facility, which was thought to be excessive at the time. Several similar escalations occurred over the years, including the purchase of the huge facility in Florida for the 260-in. SRM program, and sites in northern and southern Nevada for other projects.

Rocket Motor Chambers and Nozzles

The first specialized solid rocket chambers were for the "Old Smoky" JATO, and consisted of oil well drill tubing swaged down to the nozzle boss diameter. This provided a very good strength to weight ratio at very low cost. Successive units used a steady progression of materials through the conventional aircraft grade steel alloys, and included M-255, D-6ac, and 18% nickel. In some cases (notably the 260-in. chamber) meticulous design, processing, and fracture toughness proved to be more important than simple strength to weight ratio. Titanium alloys (6Al 4V) were an improvement used in Minuteman, and filament wound composite structures appeared to be the next and possibly last step for at least a decade or two. Filaments progressed through several types of glass, Kevlar™, and carbon fiber with polyester and epoxy matrices. Bonding layers were required in some cases, and insulating layers to prevent heating of the case required extensive development.

Nozzles started out as simple carbon steel or copper heat-sink forms, but soon changed to combinations of layers and thicknesses of various materials such as glass, asbestos, silica, and the like. The nozzle throat and area immediately upstream were subjected to a high velocity, erosive and corrosive gas stream well above the melting point of any available materials that limit their endurance. Molybdenum and/or tungsten inserts generally extended nozzle life substantially. Although carbon-carbon three dimensionally woven bodies were found to be even better, in the early years their quality was inconsistent.

Ablative nozzle design recognizes the fact that nozzles will eventually erode, and provides small changes in grain geometry that will compensate for at least part of this progression. Reentrant or buried nozzles are located almost completely inside the aft closure, which allows more propellant to be included within a given envelope, but does cause problems with nozzle heating and TVC packaging. Other advances include several types of extendible exit cones, forced deflection concepts, and several types of variable area throat configurations.

Thrust Vector Control and Thrust Termination.

All missiles that leave the earth's atmosphere require some internal means of stabilizing or altering their trajectory, and the most attractive systems have always been those using the energy in the propulsion gas stream. In roughly chronological order thrust vector control (TVC) concepts for liquid and solid rockets include: jet vanes, jet tabs, jetavators, swivel nozzles, gimbaled nozzles, (or complete thrust chamber assemblies for liquids), rotatable skewed nozzles, hot gas (from the combustion chamber) injection downstream of the throat, injection of an inert liquid downstream of the throat, the same for a reactive injectant, use of a flexible exit cone (Lockseal, Flexseal), and use of separate TVC propulsor systems. Currently liquid injection (LITVC) and Flexseals appear to be the most attractive concepts, and all have been successfully employed.

Thrust termination techniques are usually needed for ICBMs and IRBMs. These usually consist of opening large, forward-facing ports that act to both cancel the thrust and to drop the chamber pressure enough that combustion ceases. Considerable design and development effort was required to reduce shock loading and to properly route the associated gas streams. It has recently come to light that thrust termination for ballistic missiles may no longer be needed if a suitable sophisticated trajectory-shaping program can be implemented.

Thrust Modulation

Thrust modulation is a very desirable capability for any missile powerplant that has to spend the majority of its trajectory in the atmosphere. It allows rapid acceleration to the maximum practical Mach number, followed by cruise at that speed (and probably some gliding) to the target. This gives maximum range, minimum time to target, and avoidance of damage to the missile from aerodynamic heating. A dual-thrust solid motor usually accomplishes this, but this is almost always a nonoptimum compromise.

In liquid rockets thrust modulation can be accomplished easily and accurately by either controlling the continuous flow of propellants or by rapid stop-start pulsing of the propellant flow (of hypergolic propellants) to achieve the desired total impulse. Thrust levels can be optimized in flight to meet individual mission requirements. With solid rockets, there are only two practical concepts for achieving this objective. The first is to change the (effective) nozzle throat diameter. This requires moving a plug in and out of the nozzle throat and careful tailoring of propellant pressure versus the burning rate ratio. An example of such a system is shown in Figure 4. This is obviously a very hostile environment for such a mechanical device. Aerojet did develop demonstrator versions of this concept as part of their Star Wars work, but there are no known production versions. The second approach is to stop and restart the motor numerous times (pulse motor). The duration of the "off" and "on" periods gives an approximation of thrust modulation. Hybrid rockets have also been researched for thrust modulation and other applications, but none have been used in production.

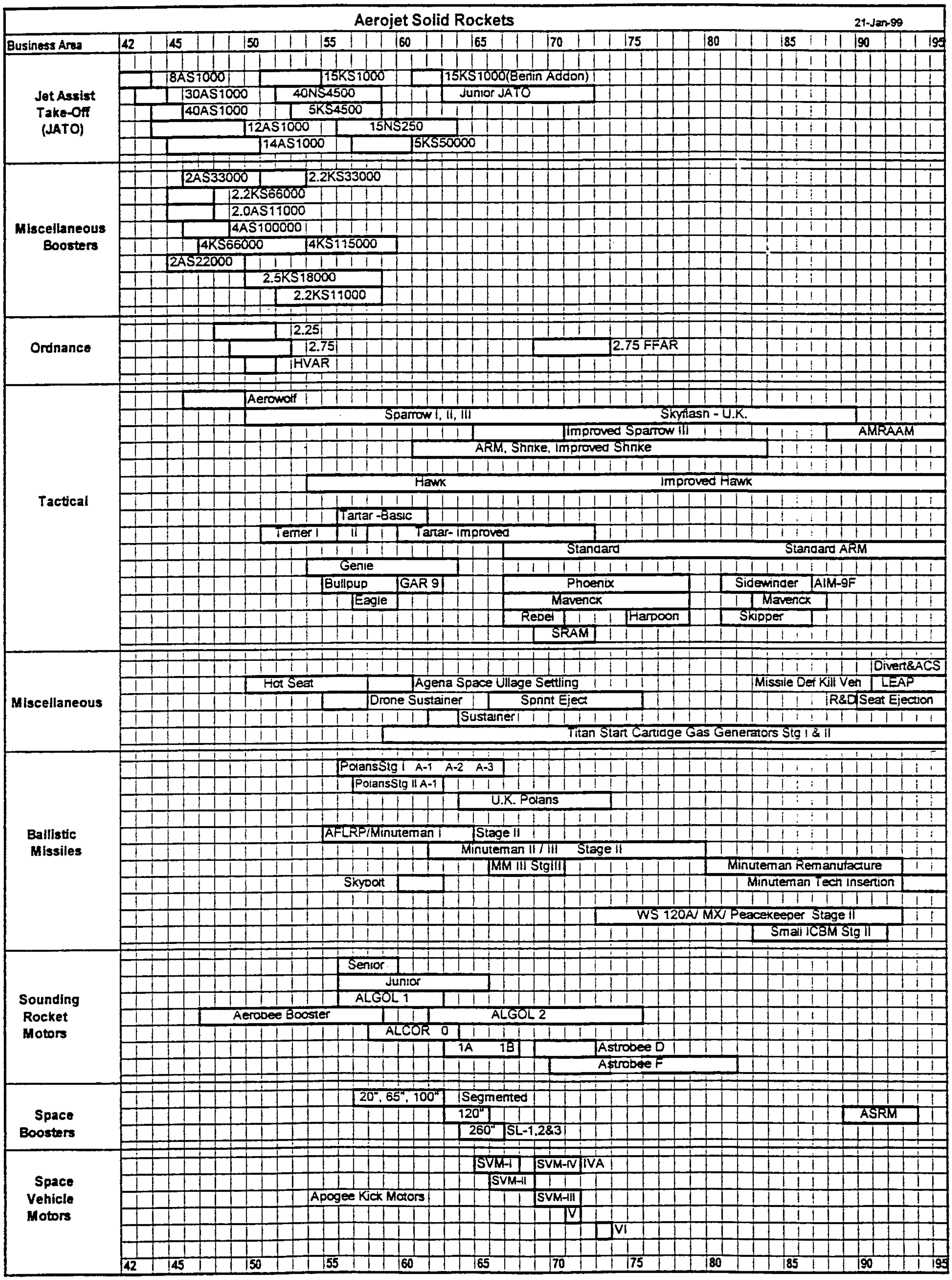
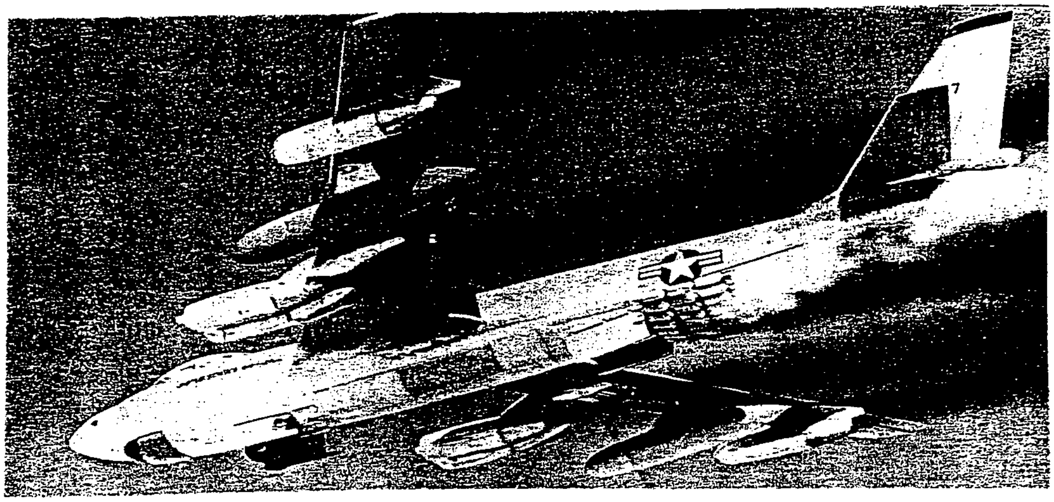
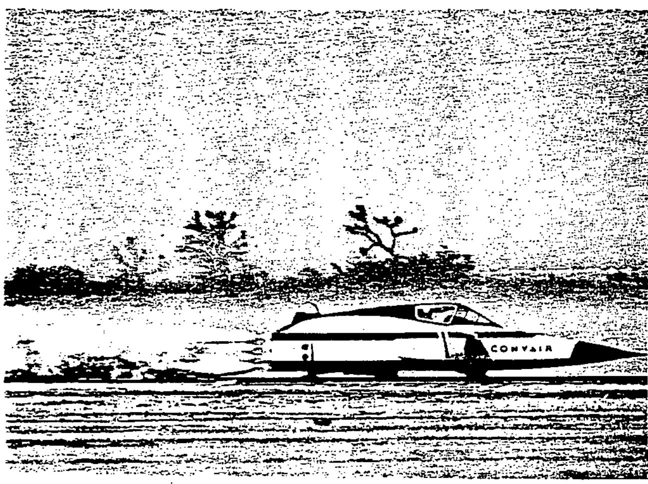
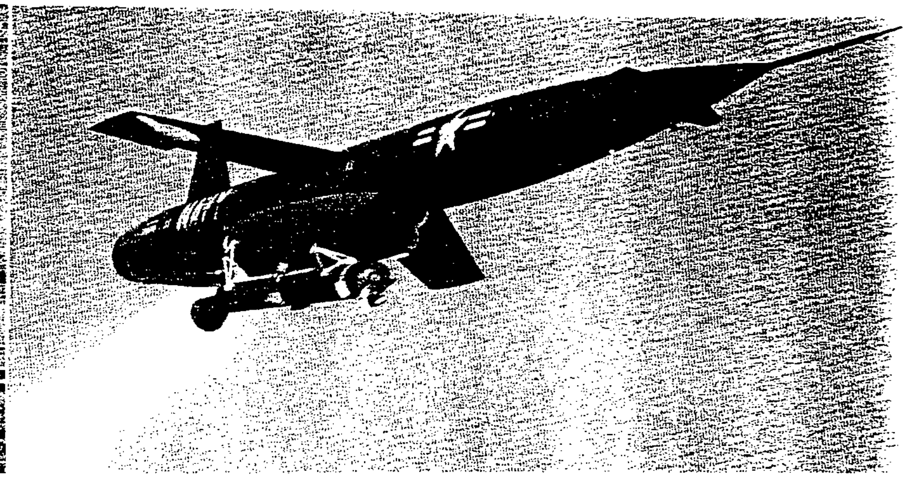
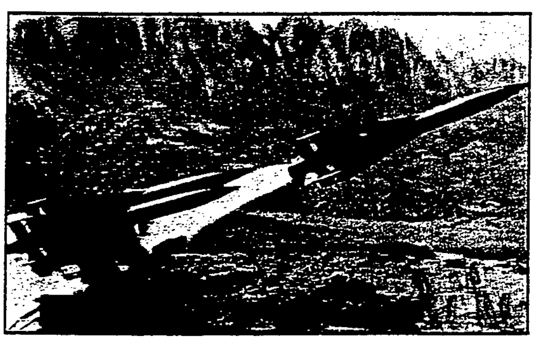

Aerojet Solid Rockets
21-Jan-99
Business Area
42 45 50 55 60 65 70 75 80 85 90 95
Jet Assist Take-Off (JATO)
8AS1000
15KS1000
15KS1000(Berlin Addon)
30AS1000
40NS4500
Junior JATO
40AS1000
5KS4500
12AS1000
15NS250
14AS1000
5KS50000
Miscellaneous Boosters
2AS33000
2.2KS33000
2.2KS66000
2.0AS11000
4AS100000
4KS66000
4KS115000
2AS22000
2.5KS18000
2.2KS11000
Ordnance
2.25
2.75
2.75 FFAR
HVAR
Tactical
Aerowolf
Sparrow I, II, III
Skyflash - U.K.
Improved Sparrow III
AMRAAM
ARM, Shrike, Improved Shrike
Hawk
Improved Hawk
Tartar -Basic
Terrier I
II
Tartar- Improved
Standard
Standard ARM
Genie
Bullpup
GAR 9
Phoenix
Sidewinder
AIM-9F
Eagle
Maverick
Maverick
Rebel
Harpoon
Skipper
SRAM
Miscellaneous
Divert&ACS
Hot Seat
Agena Space Ullage Settling
Missile Def Kill Veh
LEAP
Drone Sustainer
Sprint Eject
R&D
Seat Ejection
Sustainer
Titan Start Cartridge Gas Generators Stg I & II
Ballistic Missiles
PolarisStg I A-1 A-2 A-3
PolarisStg II A-1
U.K. Polaris
AFLRP/Minuteman I
Stage II
Minuteman II / III Stage II
MM III StgIII
Minuteman Remanufacture
Skybolt
Minuteman Tech Insertion
WS 120A/ MX/ Peacekeeper Stage II
Small ICBM Stg II
Sounding Rocket Motors
Senior
Junior
ALGOL 1
Aerobee Booster
ALGOL 2
ALCOR 0
1A
1B
Astrobee D
Astrobee F
Space Boosters
20", 65", 100"
Segmented
120"
ASRM
260"
SL-1,2&3
Space Vehicle Motors
SVM-I
SVM-IV
IVA
SVM-II
Apogee Kick Motors
SVM-III
V
VI

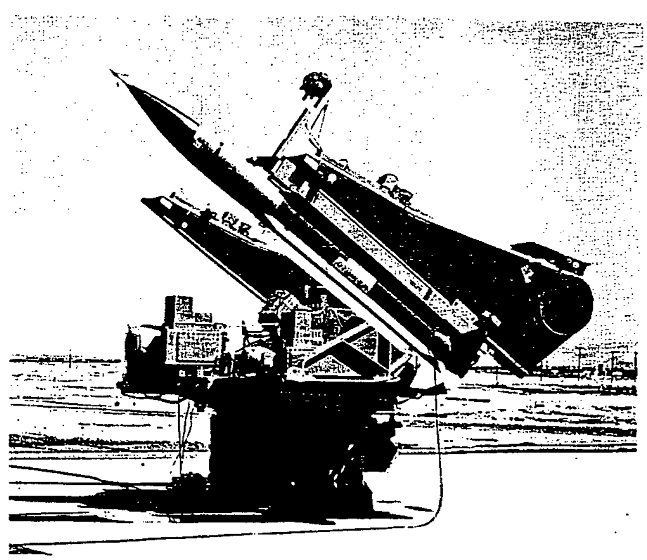
Figure 1

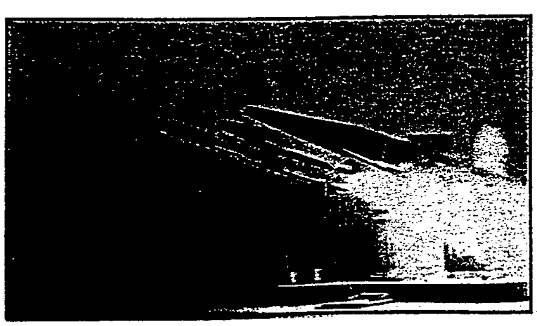












Clockwise from the top (1) B-47 Rocket Assist Takeoff using 15KS-1000s (2) Regulus II Zero length launch (3) Tartar (4) Navy Standard launch (5) Hawk launch (6) Sled propulsion

FIGURE 2

Minuteman Deliveries and Characteristiscs

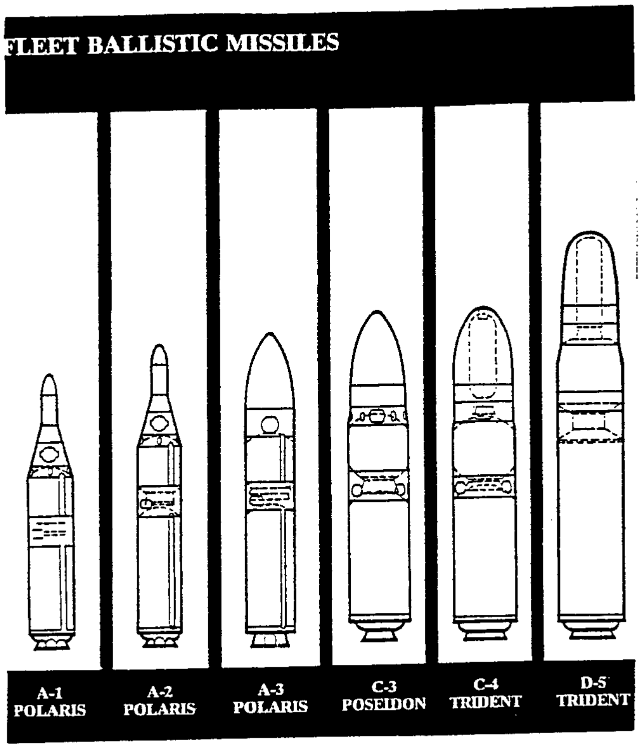
Stages	Thiokol Contractor Role	Aerojet Contractor Role	Aerojet Units R&D/Wing I/Wing II-IV	Hercules Contractor Role	Case Diam.	Case Matl.	Nozzle Type	TVC System
Minuteman I								
1	Primary				65			
1		Backup	31 / - / -		65			
2	Backup				44			
2		Primary	306 / 203 / 794		44	ST/Ti	4S	SW
3				Primary	37			
3		Parallel *	(R&D)		37			
Minuteman II								
1	Primary				65			
2		Primary	129 / 1629 / -		52	Ti	1 FB	L
3				Primary	37			
Minuteman III								
1	Primary				65			
2		Primary	(Included in MM II)		52	Ti	1 FB	L
3		Parallel	88 / 193 / -		52			
3				Primary	52			
3	Parallel **							

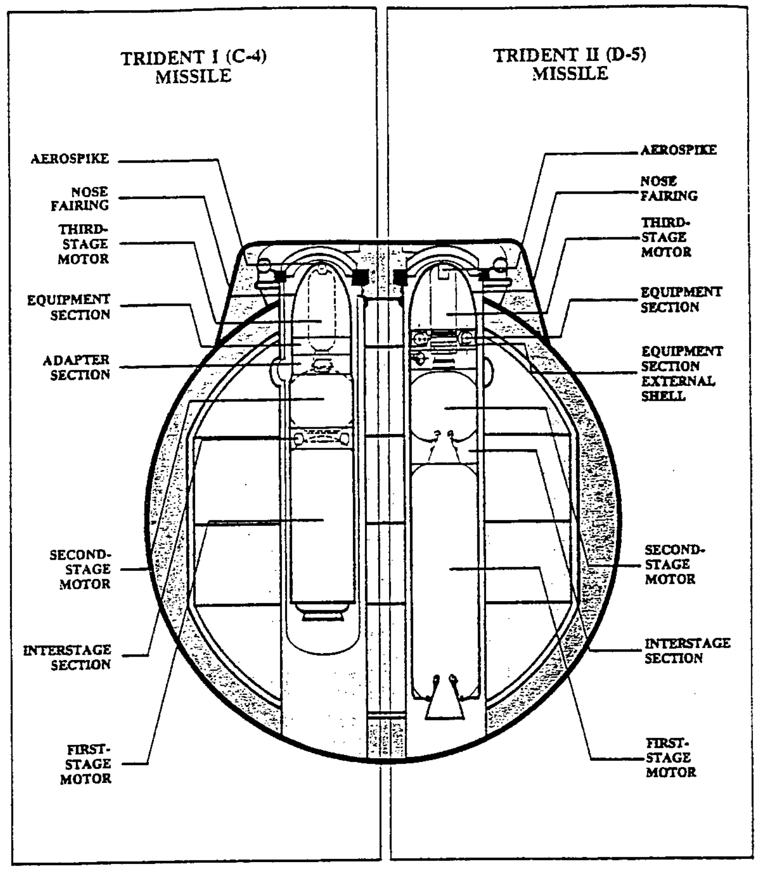
Notes:

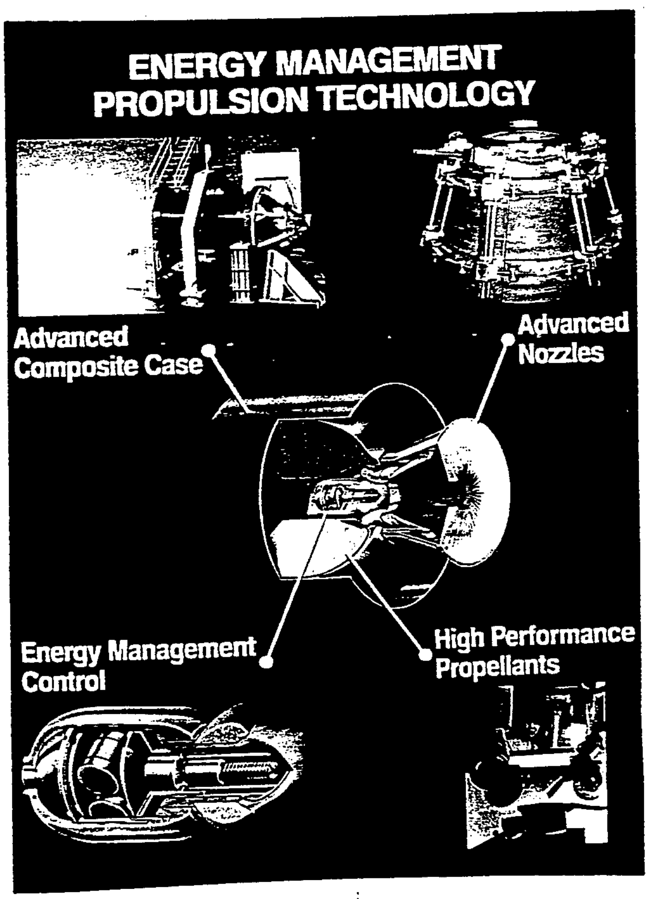
* Aerojet won initially, but Hercules won on a recompete. Aerojet continued R&D
** Thiokol won the first recompete, UTC won the second, and supplied all the operational units

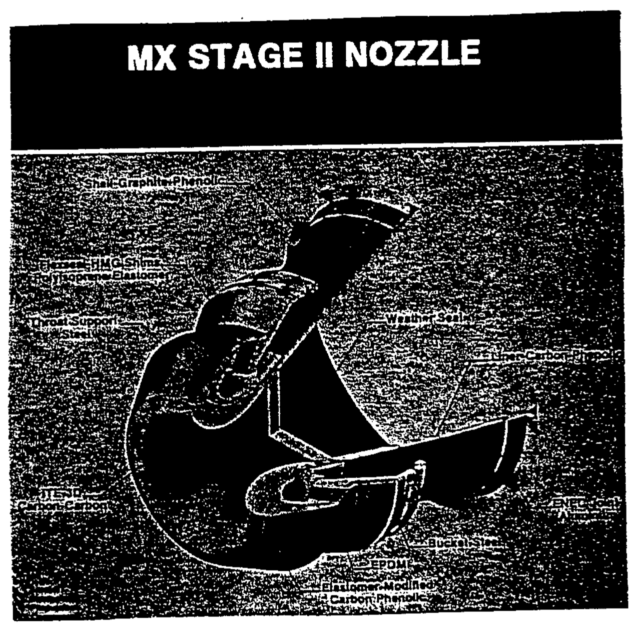
Case Diameter : inches
Case Material : ST - Steel, Ti - Titanium, G - Fiber (Glass, Kevlar, Carbon)
Nozzle Number (One or Four), and Type : F - Fixed, S - Swiveling, B - Submerged
T V C System : SW - Swiveling, L - Liquid Injection, F - Flexseal

FIGURE 3



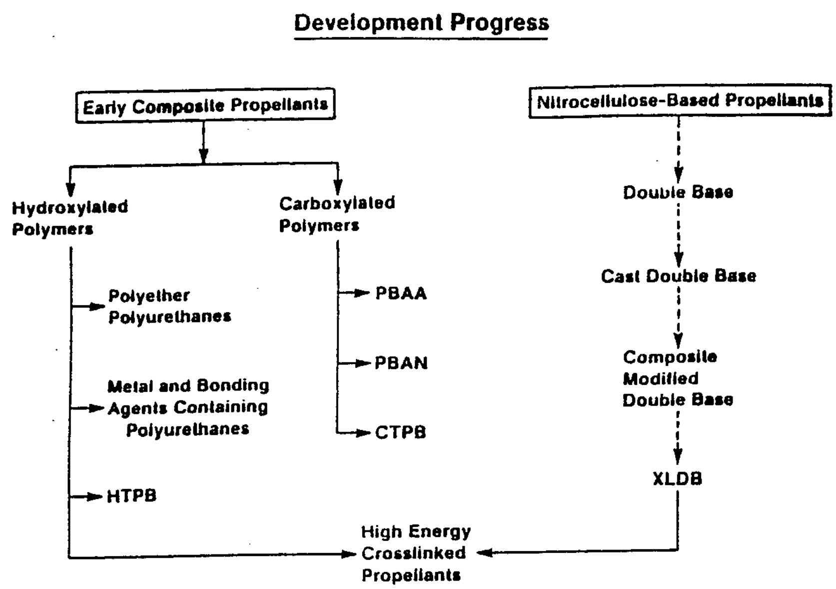






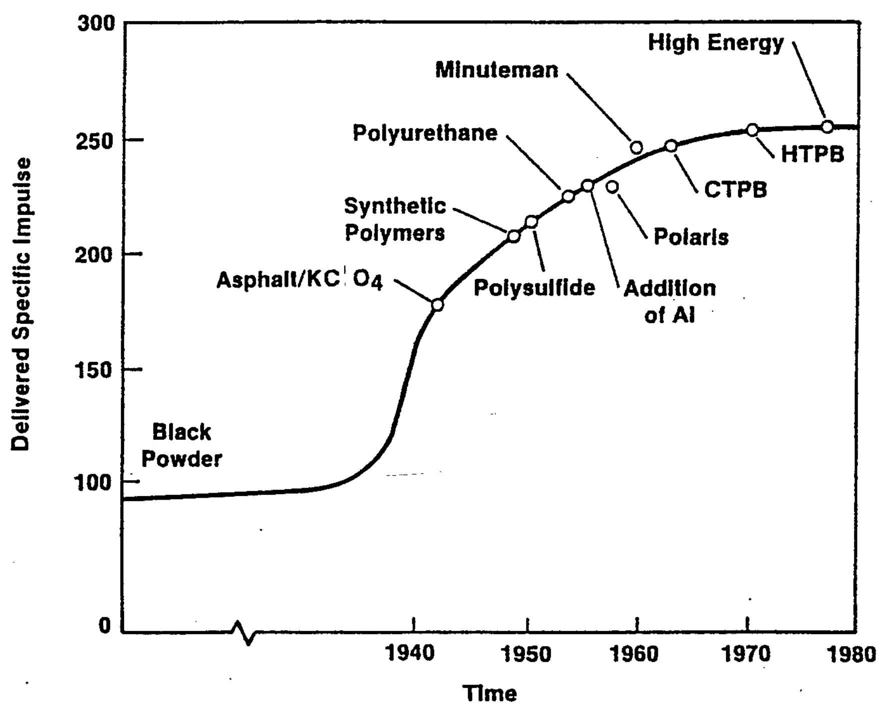
Clockwise from top left (1) FBM comparison (2) FBMs in submarine hull (3) MX Stage II nozzle high technology features (4) Miscellaneous high technology systems

FIGURE 4



History of Composite Propellants

FIGURE 5



Solid Propellant Performance History

FIGURE 6